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13. ABSTRACT (Maximum 200 words)

The long term goal of this research is to develop an improved physics-based technique for remote quantification of seafloor geoacoustical properties. The specific scientific tasks of this project were: (1) to develop inversion algorithms for estimating the sediment grain size distribution of coarse fractions in sandy sediments based on a recently developed "inclusion scattering" model, (2) to test these algorithms using the SAX04 scattering data, and (3) to provide ground truth for such tests by direct measurements of the grain size distribution in the available SAX04 sediment samples and cores. The tasks were accomplished. An algorithm for scattering data inversions was developed based on a parameterization of the grain size distribution using power law approximations in given intervals of sizes. The algorithm allows inversions of the level and power exponent of the size distribution in each interval. To provide ground truth for testing the algorithm, 13 sediment samples taken at the SAX04 site were analyzed. Sand grains and shell particles were separated and their number, weight and shape factor were measured in each size interval. It was demonstrated that the SAX04 acoustic scattering data inversion based on the developed algorithm provides a qualitative fit to the ground truth data.

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Marine sediments, grain size, geoacoustical properties, acoustic scattering, remote acoustic sensing

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Remote Sensing Technique for Geoacoustic Characterization of Heterogeneous Marine Sediments

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LONG-TERM GOALS

The long term goal of this research is to develop an improved remote acoustic sensing technique for quantification of seafloor geoacoustical properties based on advances in physics of scattering in heterogeneous media.

OBJECTIVES

The specific scientific objective of this research is to develop inversion algorithms for estimating the sediment grain size distribution of coarse fractions in sandy sediments based on recently developed "inclusion scattering" model, to test these algorithms using the SAX04 acoustic scattering data, to provide ground truth for such tests by direct measurements of the grain size distribution in the available SAX04 sediment samples and cores.

APPROACH

Recently, a model of acoustic scattering from discrete inclusions in marine sediments was developed under sponsorship of ONR Ocean Acoustics Program [1-3]. The model has been demonstrated as a good descriptor of seabed backscattering measured at SAX99 experiment over a wide frequency range (30 kHz to 300 kHz) at the grazing angles above the critical (which is about 30 degrees for sandy sediments). This model is considered in this research as a base for possible estimating the sediment properties from acoustic scattering measurements. The model considers discrete scatterers larger than mean grain size, such as coarse sand particles, gravel, shells, shelled animals etc, as inclusions embedded in a fluid sediment half-space with effective parameters, density, sound speed and attenuation, essentially different from those in water. The model takes into account reflection and

transmission losses at the water-sediment interface and, in a modified version, stratification of the inclusions [3].

The "inclusion scattering" model is based on a small number of measurable parameters. The critical sediment characteristic in this model is the depth-size distribution function of the inclusions. It provides an integral relationship of this function with the seabed scattering strength. If scattering is measured in a range of frequencies and directions, then the depth-size distribution function of the inclusions can be estimated using this relationship and appropriate inversion algorithms. In this research, such an approach has been tested using multi-frequency acoustic backscattering data recently obtained at the SAX04 experiment. The SAX04 acoustic experiments were accompanied by extensive environmental measurements [4]. In this research, the SAX04 environmental data have served as the ground truth and also defined certain frames for possible variations of the inversion parameters to provide a consistent estimation of the sediment grain size distribution.

WORK COMPLETED

To provide ground truth data for the scattering model and testing inversion algorithms, the PI has analyzed several sediment samples taken at the SAX04 site. Six cylindrical samples of 20 cm diameter with total volume about 11 liters were collected by divers and contained the sediment of the upper 6 cm layer. Also, a larger volume of the sediment (about 90 liters, from the upper 0 to 18 cm divided on three layers 6 cm each) was excavated during deployment of the APL-STMS1 apparatus (the cofferdam sediment). This sediment was placed in bags with 1 mm mesh and pre-sieved by shaking underwater.

For all the collected samples and the cofferdam sediment, using a set of sieves with the quarter-phi interval, the coarse fractions of sediment particles were analyzed by the grain size. Then two visually different classes of grains, sand particles and shells (mostly shell hash), were separated and their number, weight, volume, shape and material were analyzed. The size distribution and the shape factor were obtained for these two classes of particles with the sieve sizes in the 1 to 20 mm range.

The inversion of the sediment particle size distribution was carried out from the SAX04 multi-frequency acoustic backscatter data. The "inclusion scattering" model was used for this inversion with an assumption that the inclusions are distributed in the sediment volume uniformly, i.e., the sediment grain size distribution is depth-independent. Using this model, an algorithm for scattering data inversions was developed based on a parameterization of the size distribution using power law approximations in given intervals of sizes. Therefore, the inverted parameters in this algorithm are the level and power exponent in each interval.

A number of other parameters used in this model were considered as known and measured independently. For example, the sediment density, sound speed and attenuation were carefully measured by other investigators at the SAX04 experiment, and that provided a good base for description of acoustic penetration and propagation in the sediment used in the model.

Varying the parameters of the size distribution in the model parameters within certain limits, the difference between measured and calculated backscatter was minimized. The corresponding values of the inverted parameters were used in a multi-power law estimate for the grain size distribution function that was compared with the ground truth data.

RESULTS

The analysis of the SAX04 sediment samples has shown [5] that shells have very different properties than surrounding particulate of sand itself (mainly quartz particles). This is illustrated in Figure 1 and 2. In Figure 1, for example, it is demonstrated that the slope of the size (volume) distribution of shells is very different (much flatter) than for sand particles of the same equivalent size (decreasing steeply as the size increases), and therefore shells become a dominating coarse fraction of the sediment for particles with equivalent radius larger than 1 mm.

The results for coarse sand and shells, shown in Figure 1, were obtained taking into account analysis of the shape factor of the particles which was defined as a ratio of the estimated weight for the spherical particle (with the same density and given sieve size) to the measured weight of this particle. An alternative (but equivalent) definition for the shape factor, SF, is $SF=(d/2a)^3$, where d and a are respectively the sieve size and equivalent radius of the particle. Results of this analysis of the shape factor are illustrated in Figure 2. It is seen that shells are essentially non-spherical with a shape factor about four and larger while sand particles are much more round.

Such a difference of shapes also might be important for an explanation of the fact that the spatial variability of shells concentration at SAX04 appears to be stronger than for the sand particles of the same equivalent size, which can be seen in Figure 1 by comparison of results for different samples and the cofferdam sediment. This effect might be due to stronger and more complex interaction of non-spherical particles with hydrodynamics near the seabed (that can be important in the sediment dynamics and transport).

Generally, shells can be considered as a separate mode in the size distribution dominating at the large grain sizes (with equivalent radius larger than 1 mm), or as a sparse suspension of non-spherical inclusions in the more homogeneous and uniform substrate of densely packed more round and smaller sand particles. This mode has its own properties and parameters different from other modes (e.g., different slope and level of the size distribution as it is seen in Figure 1).

Although the current version of the "inclusion scattering" model [1-3] does not take into account the case of non-spherical shape of shells, an attempt has been made to apply this model to analysis of the SAX04 acoustic scattering data. First results have shown that the model is capable of providing a reasonable interpretation of frequency-angular dependencies of the backscattering strength. An example of the frequency dependence is given in Figure 3 for the grazing angle 35 degrees [6]. It is seen that it has two different slopes at low and high frequencies (bi-power law dependence). The analysis has shown that such dependence can be explained if the sediment grain size distribution for coarse fractions follows also the bi-power law dependence. Considering the two power exponents and the level of the size distribution as free parameters, the difference between measured and calculated

backscatter was minimized. The result for the theoretical frequency dependence is shown in Figure 3 by the solid line.

The corresponding values of the inverted parameters were used in a bi-power law estimate for the grain size distribution function which is shown in Figure 1 by the solid blue curve. It is seen from comparison with the ground truth data in Figure 1 that the acoustic data inversion provides a qualitative fit to the ground truth data. However, the level of the inverted volume size distribution for shells is higher than average for the ground truth data (although not in contradiction with the data). The reasons for such quantitative discrepancy can be that assumptions made for the model of scattering are too strong. It is clear now that the model needs some modifications to enhance its capabilities for acoustic data inversions. It can be particularly important for analysis of scattering data to be obtained in future experiments.

In the current version of the "inclusion scattering" model [1-3], used in this research for the SAX04 data analysis and inversions, the following assumptions have been made:
- Inclusions were considered as fully buried in the sediment assuming that contribution of particles located near the interface (including those partially buried) is not important;
- Inclusions were considered as spheres assuming that scattering function for a non-spherical particle can be approximated by that for a spherical one with the equivalent radius (with the same volume).

These assumptions may be the reason that the SAX04 data inversions do not provide the desirable quantitative fit to the ground truth data.

In order to eliminate these assumptions and improve inversion capabilities of the scattering model, correspondent modifications are required. For example, elimination of the first assumption is necessary to take into account scatterers located on the bottom surface [7]. It can be especially important at higher frequencies and sub-critical grazing angles because of smaller sound penetration of the sediment and respectively decreased role of the buried scatterers. Elimination of the second assumption is important for better description of the angular dependence of scattering which is known to be very sensitive to the shape of the scatterers (the so-called aspect-effect) that is commonly used in remote sensing (see, e.g., [8-10]).

IMPACT/APPLICATIONS

This research will contribute to development of an improved remote acoustic sensing technique for quantification of seafloor geoacoustical properties. The results of this work are used currently for the SAX04 data analysis funded by ONR-OA. These results are proposed to be used also for analysis of acoustic and environmental data in future experiments and further development of remote sensing techniques. In particular, these results can provide a base for modifications of inversion technique using angular dependencies of seabed scattering (obtained, e.g., with multi-beam sonar). Such a technique can be used, for example, in the follow-on analysis for the Ripple DRI 2007 Martha's Vineyard field experiment, where a wide angular range, from shallow grazing angles to near normal incidence, will be used.

RELATED PROJECTS

This research is closely related to projects providing environmental and acoustic data analysis and modeling for the ONR-OA SAX04 and ONR-CG Ripple DRI programs. In particular, this research is related to the PI's project "High Frequency Scattering from Heterogeneous Rough Sea Beds at Shallow Grazing Angles" currently funded by ONR, Ocean Acoustics. This work was conducted in collaboration with investigators at the APL-UW and NRL (Drs. K. Williams, M. Richardson, K. Briggs and others).

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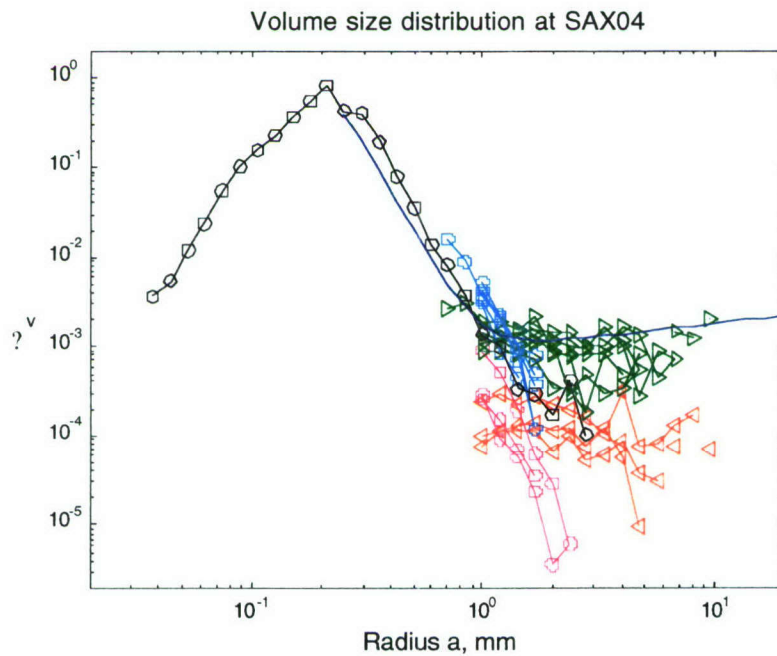
Figure 1. *Volume size distribution for the SAX04 sediment. The bold (black) -o- line shows average over 22 sediment cores, each of 6 cm diameter [Briggs]. The light lines and symbols are obtained from analysis [Ivakin] of coarse sand fractions (-o-) and shells (-< - and -> -): cyan and green ones are for the five XBAMS and one SAS sediment samples (each of 20 cm diameter) and magenta and red ones are for three layers of the cofferdam sediment. The solid blue line corresponds to the bi-power law function.*
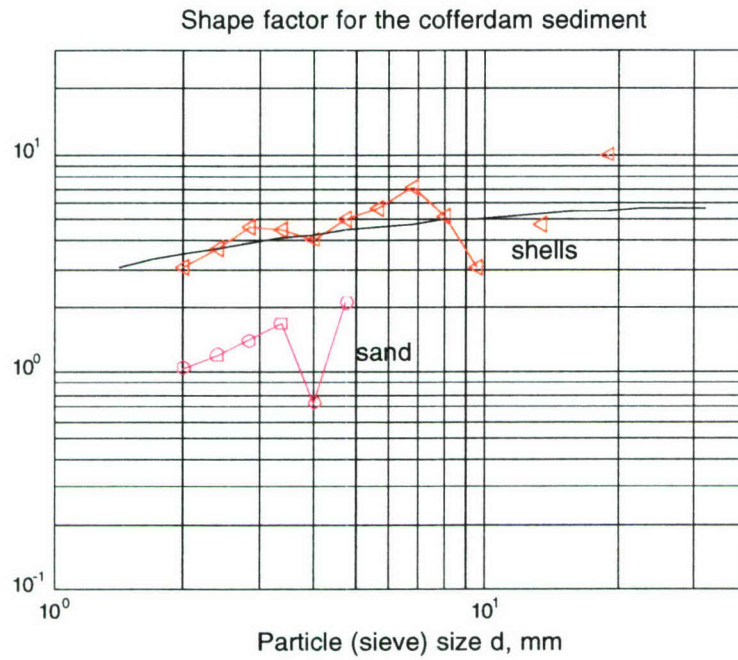
Figure 2. *The shape factor for the SAX04 sediment grain size distribution of coarse sand and shell fractions. The solid line approximates the shape factor for shells.*
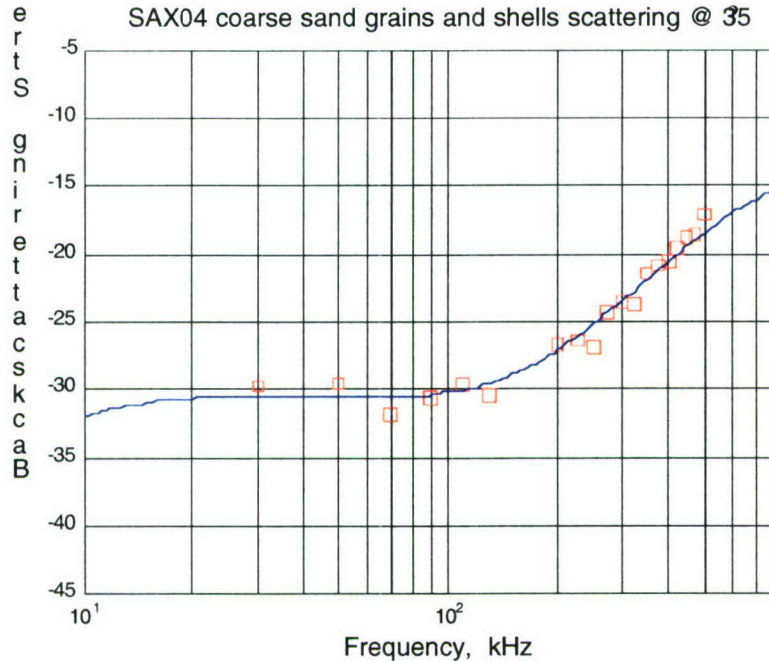

Figure 3. *Frequency dependence of the bottom backscattering strength at SAX04 (squares) at the grazing angle 35 degrees. The solid line shows results of calculations using the inclusion scattering model with the bi-power law grain size distribution (see solid line in Figure 1).*